Charmed Baryon Spectroscopy from CLEO at CESR

M. Sajjad Alam

University at Albany and CLEO Collaboration
Physic Department, S.U.N.Y.A., Albany, NY 12222

Abstract. Charmed baryon spectroscopy has been unfolding since the discovery of the first charmed baryon in 1975. The Cornell Electron Storage Ring (CESR) has now established itself as a charmed particle factory. In this report, we present results on charmed baryon production at CESR using the CLEO detector.

INTRODUCTION

The discovery of J/ψ mesons at BNL[2] and SLAC[1] in 1974 heralded the era of particles containing a new quark carrying the charm quantum number and named the c quark. Immediately a rich, new spectroscopy of mesons and baryons containing the charm quark became possible. The first open charm mesons $D^0(c\bar{u})$ and $D^+(c\bar{d})$ were observed in 1976, and first evidence[3] for the ground state charm baryon $\Lambda_c^+(cud)$ appeared as a single neutrino interaction event in a bubble chamber at BNL in 1975. Soon clear signals for Λ_c^+ were observed in πp and in e^+e^- interactions at FNAL[6] and SLAC[7] ,respectively.

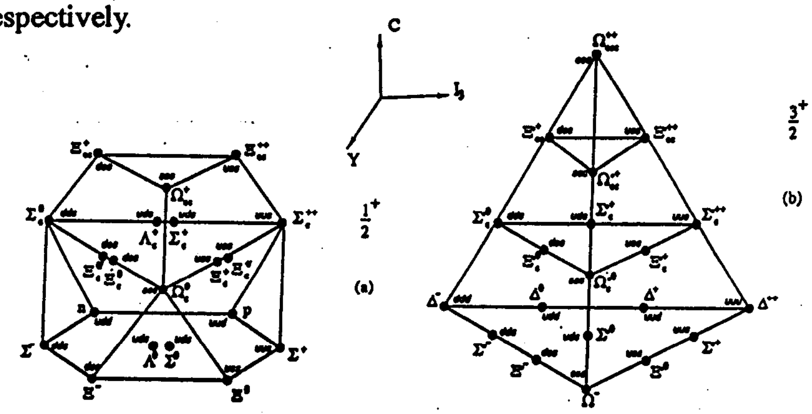

Figure 1. The ground state charmed baryon $J^P = \frac{1}{2}^+$ and $J^P = \frac{3}{2}^+$ multiplets.

Twenty five years after the observation of the first charmed baryon, charmed baryon spectroscopy is still unfolding. Just as the ground state meson nonets expanded to sixteen-plets, the ground state $J^P = \frac{1}{2}^+$octet and $J^P = \frac{3}{2}^+$decuplet of baryons expanded to a 20-plet in each case. They are shown in Figure 1.

At CESR, there are two ways that charmed baryons are produced. The virtual photon produced in e^+e^- annihilations from the continuum couple to $c\bar{c}$ pairs, which then hadronize into charmed mesons and baryons. Charmed baryons can also be produced from the secondary decays of $B/\bar{B}$ mesons produced at the $\Upsilon(4S)$. Let us define the production variable $x_p = p/p_{max} = p/(\sqrt{E^2 - m^2})$, where p is the momentum of the particle and p_{max} its maximum value. E_b is the beam energy and m the mass of the charmed baryon under study. From measurements of continuum production of charmed mesons[12], it has been observed that 60% of charmed baryons produced from the continuum have $x_p > 0.5$. Charmed baryons produced from the secondary decays of $B/\bar{B}$ mesons are kinematically limited to x_p less than about 0.4 - 0.5 depending on the charmed baryon being considered. To avoid combinatorial background from low momentum combinations and only focus on continuum production, all CLEO analyses for charmed baryon studies have $x_p > 0.5$, typically.

THE LOWEST MASS $\Lambda_c^+(cud)$ CHARMED BARYON

Since the Λ_c^+ is the lowest mass charmed baryon, it can only decay weakly. A wide variety of final states are accessible through tree level spectator, exchange and annihilation diagrams corresponding to the $c \to sW^+$ coupling. In 1991, CLEO[16] published continuum production of the Λ_c^+ in the decay modes $pK^-\pi^+$, $p\overline{K^0}$, $p\overline{K^0}\pi^+\pi^-$, $\Lambda\pi^+$, $\Lambda\pi^+\pi^-\pi^+$, and $\Xi^-K^+\pi^+$ from about 430 pb^{-1} of data around the $\Upsilon(4S)$ and the $\Upsilon(5S)$. As an example, Figure 2(a) shows the mass distributions corresponding to $pK^-\pi^+$ combinations with $x_p > 0.5$ with a fitted signal area of 512 ± 50 events. The weighted mass from fits to the mass distributions in all the above decay modes was reported to be $2284.7 \pm 0.6 \pm 0.7\ MeV/c^2$. Fitting to the Peterson[9] fragmentation function is a standard approach to parametrizing the shape of the x_p production spectrum in terms of the variable ϵ_Q. CLEO[16] has measured a value of $\epsilon_Q = 0.29 \pm 0.05$ from a fit to the x_p spectrum as shown in Figure 2(b).

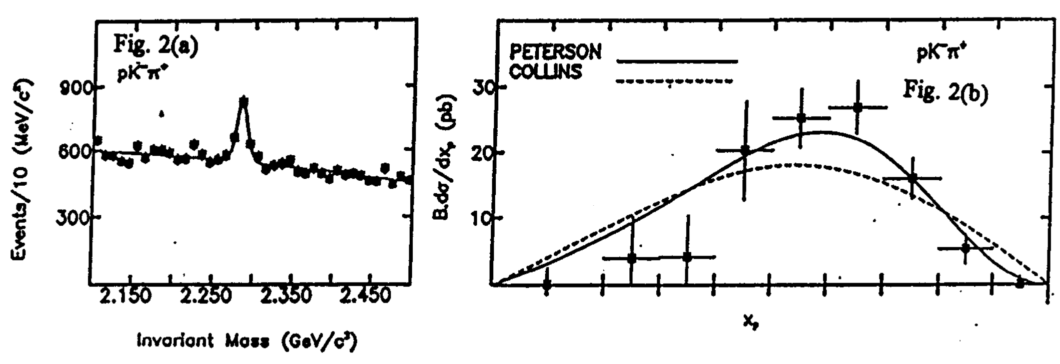

Figure 2. (a) Inv. mass distr. for $pK^-\pi^+$ combinations with x_p>0.5. (b) x_p production spectrum with Peterson Function fit.

Using the inclusive decay $B \to \Lambda_c^+ X$ and assuming that all light baryons pro-

TABLE 1(a). Λ_c^+ Decay Modes		TABLE 1(b). Λ_c^+ Decay Modes Continued	
Decay Modes	**Relative BR.**	**Decay Modes**	**Relative BR.**
$pK^-\pi^+$[16]	1.0	$pK^-\pi^+$[16]	1.0
pK^0	$0.44 \pm 0.07 \pm 0.05$	$p\phi$ [38]	$0.039 \pm 0.009 \pm 0.007$
$p\overline{K^0}\pi^+\pi^-$	$0.43 \pm 0.12 \pm 0.04$	$\Sigma^+ \pi^0$ [22]	$0.20 \pm 0.03 \pm 0.03$
$\Lambda\pi^+$	$0.18 \pm 0.03 \pm 0.03$	$\Sigma^+ \varpi$	$0.54 \pm 0.13 \pm 0.06$
$\Lambda\pi^+\pi^-\pi^+$	$0.65 \pm 0.11 \pm 0.12$	$\Sigma^+ \pi^+\pi^-$	$0.74 \pm 0.07 \pm 0.09$
$\Xi^- K^+\pi^+$	$015 \pm 0.04 \pm 0.03$	$\Sigma^+ \rho^0$	< 0.27
$\Sigma^+K^+K^-$ [21]	$0.07 \pm 0.011 \pm 0.011$	$\Lambda\pi^+\pi^0$ [23]	$0.73 \pm 0.09 \pm 0.16$
$\Sigma^+ \phi$	$0.07 \pm 0.020 \pm 0.016$	$\Sigma^0\pi^+\pi^0$	$0.36 \pm 0.09 \pm 0.10$
$\Xi^0 K^+$	$0.08 \pm 0.013 \pm 0.013$	$\Sigma^0\pi^+\pi^-\pi^+$	$0.21 \pm 0.05 \pm 0.05$
$\Xi^- K^+\pi^+$	$0.08 \pm 0.014 \pm 0.014$	$\Sigma^0\pi^+$	$0.21 \pm 0.02 \pm 0.04$
$\Xi^{*0}\pi^+$	$0.05 \pm 0.016 \pm 0.010$	$p\overline{K^0}\eta$ [28]	$0.25 \pm 0.04 \pm 0.04$
$pK^-\pi^+\pi^0$ [40]	$0.67 \pm 0.04 \pm 0.11$	$\Lambda\pi^+\eta$	$0.35 \pm 0.05 \pm 0.06$
$p\overline{K^0}$	$0.46 \pm 0.02 \pm 0.04$	$\Sigma^+\eta$	$0.11 \pm 0.03 \pm 0.02$
$p\overline{K^0}\pi^+\pi^-$	$0.52 \pm 0.04 \pm 0.05$	$\Sigma^{*+}\eta$	$0.17 \pm 0.04 \pm 0.3$
$p\overline{K^0}\pi^0$	$0.66 \pm 0.05 \pm 0.07$	$\Lambda\overline{K^0}K^+$	$0.12 \pm 0.02 \pm 0.02$
		$\Lambda l^+\nu_l$ [26]	$0.52 \pm 0.03 \pm 0.09$
Absolute Branching Fraction: $Br\,(\Lambda_c^+ \to pK^-\pi^+) = (4.3 \pm 1.0 \pm 0.8)\%$			

duced in a B meson decays are from the secondary decay of predominantly the charmed baryon Λ_c^+ and that Ξ_c's decays are negligible, CLEO[18] has estimated the absolute branching fraction $Br(\Lambda_c^+ \to pK^-\pi^+)$ to be $(4.3 \pm 1.0 \pm 0.8)\%$. A similar result has also been obtained by ARGUS using similar model assumptions. Since then, CLEO has observed several decay modes of the Λ_c^+; these measurements are summarized in Table 1(a) and (b).

OBSERVATION OF Σ_c^{++}, Σ_c^+, AND Σ_c^0

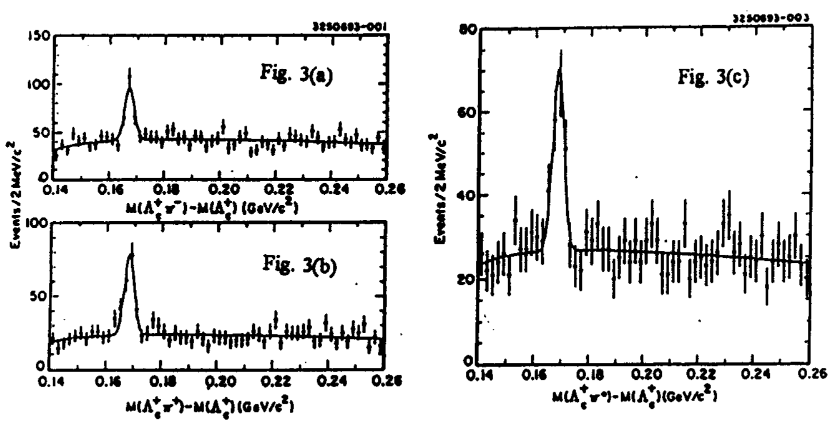

Figure 3. Inv. Mass difference distributions for $\Lambda_c\pi$ combinations relative to Λ_c.

The first evidence of the Σ_c^{++} (cuu) was reported as a single bubble chamber event[3] in 1975 observed as $\nu p \to \mu^-\Sigma_c^{++} \to \mu^-\Lambda_c^+\,\pi^+ \to \mu^-\,(\Lambda\pi^+\pi^-\pi^+)\,\pi^+$. The neutral

$\Sigma_c^0(cdd)$ was first produced[6] in γ Be collisions in 1976. For a long time, the only evidence for the Σ_c^+ (cud) was a single νp interaction observed in the Big European Bubble Chamber at CERN in 1980[8]. The first observations of Σ_c^{++} and Σ_c^0 at CESR were presented by CLEO[13] in 1989 using about 418 pb^{-1}of data in the region of the $\Upsilon(4S)$. A more precise measurement[20] was presented in 1993 using 1.48 fb^{-1}, which also included the first convincing evidence for the Σ_c^+ observed in the decay mode $\Lambda_c^+\pi^0$. In Figures 3 (a), (b), and (c) are shown the mass difference distributions $M(\Lambda_c\pi) - M(\Lambda_c^+)$ for the $\Sigma_c^{++}, \Sigma_c^+$, and Σ_c^0, respectively. From a fit to these mass difference distributions, the corresponding mass differences are measured to be $168.2 \pm 0.3 \pm 0.2, 168.5 \pm 0.4 \pm 0.2$, and $167.1 \pm 0.3 \pm 0.2$ MeV/c^2, respectively. It may be noted that the $\Lambda_c^+(c[u,d])$ and the $\Sigma_c^+(c\{u,d\})$ have the same quark structure, but the wave functions are antisymmetric (denoted by $[u,d]$) and symmetric (denoted by $\{u,d\}$) with respect to the interchange of the light quarks, respectively. This sets the scale of mass splitting for the two light quarks to be in the antisymmetric or symmetric configurations.

OBSERVATION OF $\Xi_c^+(csu)$ AND $\Xi_c^0(csd)$

The charmed strange baryon Ξ_c^+ was first (1983) observed[10] in Σ^- + Be collisions at CERN at a mass of 2460 ± 25 MeV/c^2 in the decay mode $\Lambda K^-\pi^+\pi^+ + X$. Its isospin partner, the Ξ_c^0 was first (1989) observed[14] at CESR in e^+e^- collisions in the decay mode $\Xi^-\pi^+$ at a mass of $2471 \pm 3 \pm 4$ MeV/c^2.

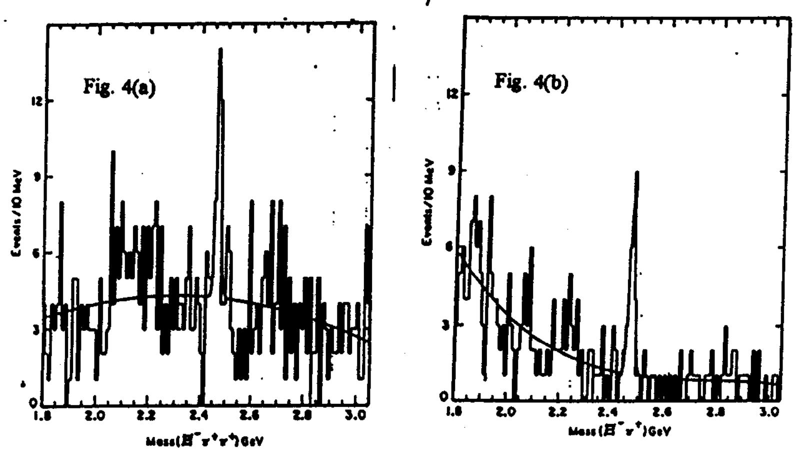

Figure 4. Inv. mass distrib. for $\Xi^-\pi^+\pi^+$ and $\Xi^-\pi^+$ combinations with x_p >0.5.

Using a larger data sample of 430 pb^{-1} of data in the region of the $\Upsilon(4S)$, CLEO reported in 1989 the first observation[15] of Ξ_c^+ in e^+e^- collisions in the decay mode $\Xi^-\pi^+\pi^+$ at a mass of $2467 \pm 3 \pm 4$ MeV/c^2. In the same experiment, the isospin mass-splitting of the Ξ_c^+ relative to Ξ_c^0 was measured to be $\Delta M = -5 \pm 4 \pm 1$ MeV/c^2 and the production cross-sections were measured to be $\sigma.Br(\Xi_c^0 \to \Xi^-\pi^+) = 0.39 \pm 0.1$ pb for the Ξ_c^0 and $\sigma.Br(\Xi_c^+ \to \Xi^-\pi^+\pi^+) = 0.57 \pm 0.16$ pb for the Ξ_c^+ with $x_p > 0.5$ for both cases. In Figures 4 (a) and (b), we show the mass distributions for $\Xi^-\pi^+\pi^+$

and $\Xi^-\pi^+$ combinations with $x_p > 0.5$, where fitting yields signal sizes of 23.0 ± 6.3 and 18.8 ± 4.9 events corresponding to Ξ_c^+ and Ξ_c^0, respectively.

Since then, CLEO has observed the Ξ_c^+ in several decay modes[37],[41] and relative to the $\Xi^-\pi^+\pi^+$ decay mode, branching fractions for the decay modes $\Xi_c^+ \rightarrow \Sigma^+K^-\pi^+$, Σ^+K^{*0}, $\Lambda K^-\pi^+\pi^+$, $\Xi^0\pi^+$, $\Xi^0\pi^+\pi^0$, and $\Xi^0\pi^+\pi^-\pi^+$ have been measured to be $1.18 \pm 0.26 \pm 0.17$, $0.92 \pm 0.27 \pm 0.14$, $0.58 \pm 0.16 \pm 0.07$, $0.55 \pm 0.13 \pm 0.09$, $2.34 \pm 0.57 \pm 0.37$, and $1.74 \pm 0.42 \pm 0.27$, respectively. A fit to x_p production spectrum of the Ξ_c^+ with the Peterson function yields $\epsilon_Q = 0.23^{+0.06}_{-0.05} \pm 0.3$.

CLEO has also observed[17] the Ξ_c^0 in the decay modes Ω^-K^+, $\Xi^-\pi^+\pi^0$, $\Xi^0\pi^+\pi^-$ and $\Xi^-\pi^+\pi^-\pi^+$. The branching fractions for these modes relative to that into $\Xi^-\pi^+$ have been measured to be $0.51 \pm 0.21 \pm 0.05$, $3.0 \pm 0.6 \pm 0.5$, $2.2 \pm 0.6 \pm 0.4$, $1.8 \pm 0.6 \pm 0.5$, respectively. The last three measurements are preliminary. CLEO has also observed[29] the decay modes $\Xi_c^+ \rightarrow \Xi^0 e^+\nu_e$ and $\Xi_c^0 \rightarrow \Xi^- e^+\nu_e$ using $\Xi - e^+$ correlations. They have measured $Br(\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+)/Br(\Xi_c^+ \rightarrow \Xi^0 e^+\nu_e)$ and $Br(\Xi_c^0 \rightarrow \Xi^-\pi^+)/Br(\Xi_c^0 \rightarrow \Xi^- e^+\nu_e)$ to be $0.44 \pm 0.11^{+0.11}_{-0.06}$ and $0.32 \pm 0.10^{+0.05}_{-0.03}$, respectively. Further, assuming Ξ_c^+ and Ξ_c^0 production to be equal in e^+e^- collisions, the lifetime ratio of Ξ_c^+ to Ξ_c^0 is estimated to be $2.46 \pm 0.70^{+0.33}_{-0.23}$. Using the world measurement of Ξ_c lifetimes, and the semileptonic branching fraction measurements, the absolute branching fractions $Br(\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+)$ and $Br(\Xi_c^0 \rightarrow \Xi^-\pi^+)$ are estimated to be $f_c(2.1 \pm 0.8 \pm 0.4)\%$ and $f_c(0.43 \pm 0.15 \pm 0.10)\%$, respectively. The factor $f_c = Br(\Xi_c \rightarrow \Xi l^+\nu_l)/Br(\Xi_c \rightarrow X l^+\nu_l)$ and is expected from theoretical models to be between 0.6 to 1.0.

OBSERVATION OF $\Xi_c^{+\prime}$ AND $\Xi_c^{0\prime}$

The charmed strange baryons $\Xi_c^{+\prime}(c\{s,u\})$ and $\Xi_c^{0\prime}$ $(c\{s,d\})$ have the same quark content as the $\Xi_c^+(c[s,u])$ and $\Xi_c^0(c[s,u])$, but their wave-functions are symmetric under interchange of the light quarks. The mass difference of $\Xi_c^{\prime}$ relative to Ξ_c baryons is predicted[32] [35] to be between $100 - 110$ MeV/c^2; consequently, only photonic transitions between them are possible. Based on 4.96 fb^{-1} of data in the region of the $\Upsilon(4S)$, CLEO observes a yield of (225 ± 21) Ξ_c^+ events in the decay modes $\Xi^-\pi^+\pi^+$, $\Xi^0\pi^+\pi^0$ and (289 ± 44) Ξ_c^0 events in the decay modes $\Xi^-\pi^+$, $\Xi^-\pi^+\pi^0$, Ω^-K^+, and $\Xi^0\pi^+\pi^-$. Combinations are formed of above Ξ_c^+ and Ξ_c^0 candidates with clean and isolated photons with energy greater than 100 MeV. In Figures 5 (a) and (b), we show the mass difference distributions $\Delta M^+ = M(\Xi_c^+\gamma) - M(\Xi_c^+)$ and $\Delta M = M(\Xi_c^0\gamma) - M(\Xi_c^0)$, where the contributions from the different decay modes have been added. Fitting to the observed mass enhancements in these figures yields signal areas of (25.5 ± 6.5) and (28.0 ± 7.1) events, respectively. The mass difference peaks are measured to be $\Delta M^+ = (107.8 \pm 1.7 \pm 2.5)$ MeV/c^2 and $\Delta M^- = (107.0 \pm 1.4 \pm 2.5)$ MeV/c^2. Since the Ξ_c^{*+} and Ξ_c^{*0} have already been observed, the most likely interpretation of the above resonances would be as the $J^P = \frac{1}{2}^+$ charmed strange baryons $\Xi_c^{+\prime}$ and $\Xi_c^{0\prime}$, respectively. A fit to the x_p production spectrum averaged over the two charged states with the Peterson function yields $\epsilon_Q = 0.20^{+0.23}_{-0.09} \pm 0.07$. We also measure that the fraction of Ξ_c from Ξ_c' baryons, averaged over both charged states, to be $(35 \pm 9 \pm 7)\%$.

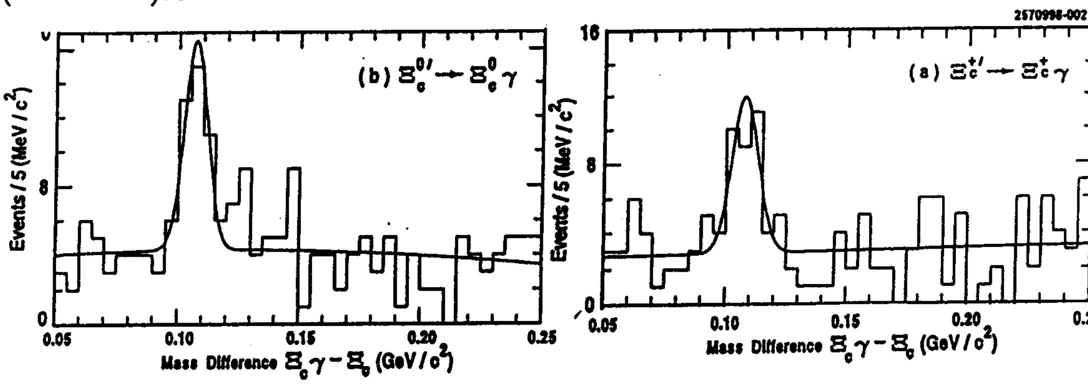

Figure 5. Inv. mass distrib. for $\Xi_c^0\gamma$ and $\Xi_c^+\gamma$ combinations with $x_p > 0.5$.

SEARCH FOR THE DOUBLY STRANGE CHARMED BARYON $\Omega_c^0(css)$

The Ω_c^0 was first reported as three events in the decay mode $\Xi^- K^- \pi^+ \pi^+$ at a mass of 2746 ± 20 MeV/c^2 from the WA62 hyperon beam experiment at CERN[11] in 1985. In e^+e^- collisions, the ARGUS collaboration was first to present evidence[19] with 12.2 ± 4.5 events in the decay mode $\Xi^- K^- \pi^+ \pi^+$ at a mass of $2719.0 \pm 7.0 \pm 2.5$ MeV/c^2. Their data sample consisted of 389 pb^{-1}. But using 1.8 fb^{-1} of data, CLEO failed to observe any events in this decay mode and placed a 90% C.L. upper limit of $\sigma.Br(\Omega_c^0 \to \Xi^- K^- \pi^+ \pi^+) < 0.4$ pb to be compared to ARGUS's reported measurement of $2.41 \pm 0.90 \pm 0.3$ pb for this value. While the observation of Ω_c^0 in e^+e^- collisions is not clear, FNAL experiment E687 has now reported observations[25] [?] of 10.3 ± 3.9 and 42 ± 9 events in the decay modes $\Omega^- \pi^+$ and $\Xi^- K^- \pi^+ \pi^+$, respectively. The masses measured from these decay modes are reported to be $2705.9 \pm 3.3 \pm 2.2$ and 2699 ± 2.9 MeV/c^2, respectively.

OBSERVATION OF THE $\Xi_c^{*0}(csd)$ AND $\Xi_c^{*+}(csu)$

In 1995, CLEO[33] reported the observation of the Ξ_c^{*0}, the $J^P = \frac{3}{2}^+$ partner of the Ξ_c^0, where the two light quarks are in spin $S = 1$ state. Following this, CLEO[34] reported the observation of its isospin partner Ξ_c^{*+} in 1996. The data sample consisted of 3.7 fb^{-1} and 4.1 fb^{-1} of data in the region of the $\Upsilon(4S)$, respectively. They were detected by forming $\Xi_c^+\pi^-$ and $\Xi_c^0\pi^+$ combinations, respectively. The Ξ_c^+ was reconstructed in the decay modes $\Xi^-\pi^+\pi^+$, $\Xi^0\pi^+\pi^0$ and $\Sigma^+ K^{*0}$, while the Ξ_c^0 was reconstructed in the decay modes $\Xi^-\pi^+$, $\Omega^- K^+$, $\Xi^-\pi^+\pi^0$ and $\Xi^0\pi^-\pi^+$. To obtain improved mass resolution, instead of the invariant mass distributions, the mass difference $\Xi_c\pi - \Xi_c$ distributions were plotted for combinations with x_p >0.4 - 0.6 depending on the decay mode of the Ξ_c used. Figures 6 (a) and (b) show the corresponding mass difference distributions with clear peaks.

For the first figure, a fit to the resonance peak yields a signal size of 54.6 ± 12.1 events at $\Delta M^+ = 178.2 \pm 0.5 \pm 1.0\ MeV/c^2$. The natural width is estimated to be $\Gamma^+ = 2.6^{+1.7}_{-1.4}\ MeV/c^2$. A fit to the measured x_p production spectrum with the Peterson function yields $\epsilon_Q = 0.22^{+.15}_{-.08}$ and extrapolating to $x_p < 0.5$,CLEO calculates that $(27 \pm 6 \pm 6)\%$ of all observed Ξ_c^+'s are produced from the secondary decays of the higher Ξ_c^{*0} states. Fitting to the second figure yields a signal size of $34.2^{+8.9}_{-7.9}$ events at $\Delta M^0 = 174.3 \pm 0.5 \pm 1.0\ MeV/c^2$ with natural width $\Gamma^0 < 3.1\ MeV/c^2$. The Peterson function fit to the x_p production spectrum gives a value of $\epsilon_Q = 0.23^{+0.06}_{-0.05} \pm 0.03$ and using it to extrapolate the measured spectrum below $x_p < 0.5$, the fraction of Ξ_c^0's produced from the secondary decays of Ξ_c^{*+} baryons is calculated to be $(17 \pm 5^{+4}_{-3})\%$.

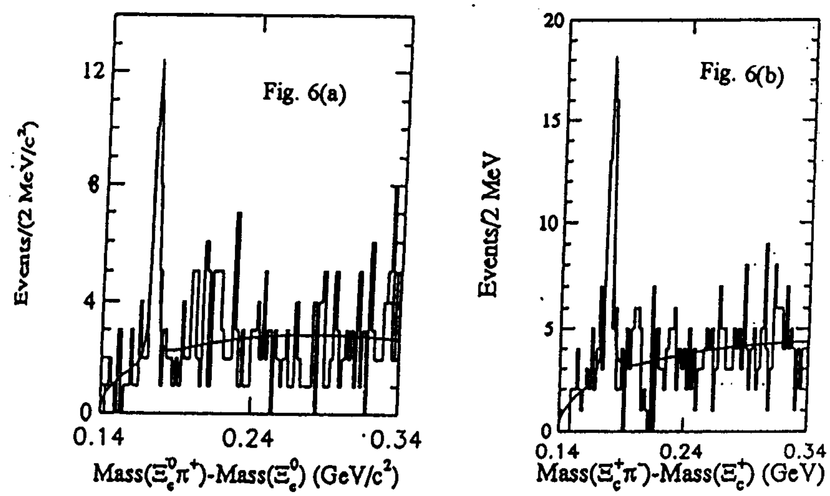

Figure 6. Inv. mass difference distrib. for (a) $\Xi_c^0\pi^+$ and (b) $\Xi_c^+\pi^-$ combinations relative to Ξ_c^0 and Ξ_c^+ combinations.

OBSERVATION OF Σ_c^{*++} AND Σ_c^{*0}

The first observations of the Σ_c^{*++} and Σ_c^{*0} were reported[39] by the CLEO collaboration in 1995 in the decay modes $\Lambda_c^+\pi^+$ and $\Lambda_c^+\pi^-$. Based on 4.8 fb^{-1} of data around the $\Upsilon(4S)$ region, Λ_c^+ candidates were reconstructed in thirteen different decay modes. In Figures 7 (a) and (b), the mass difference distributions for the above combinations with respect to the Λ_c^+ are plotted. In each case, a narrow peak corresponding to the $J^P = \frac{1}{2}^+$ charmed baryon Σ_c and the broader $J^P = \frac{3}{2}^+$ partner Σ_c^{**} can be seen. Fitting these peaks to a Gaussian resolution and a Breit-Wigner function for both the resonance yields signal sizes of $677^{+101}_{-93}$and 504^{+93}_{-83} events for the Σ_c^{*++} and Σ_c^{*0}, respectively. CLEO reports $\Delta M^{++} = 234.5 \pm 1.1 \pm 0.8\ MeV/c^2$ and

$\Delta M^0 = 232.6 \pm 1.0 \pm 0.8\ MeV/c^2$ with natural widths $\Gamma^{++} = 18^{+4}_{-3}\ MeV/c^2$ and $\Gamma^0 = 13^{+4}_{-3}\ MeV/c^2$. A fit to the x_p charge-averaged production spectrum with the Peterson function yields $\epsilon_Q = 0.30^{+0.10}_{-0.07}$ and extrapolating the measured spectrum to x_p <0.5, it is estimated that $(12.8^{+1.5}_{-1.3} \pm 3.2)\%$ of Λ_c^+ baryons are produced from the decay of the two Σ_c^{**} baryons.

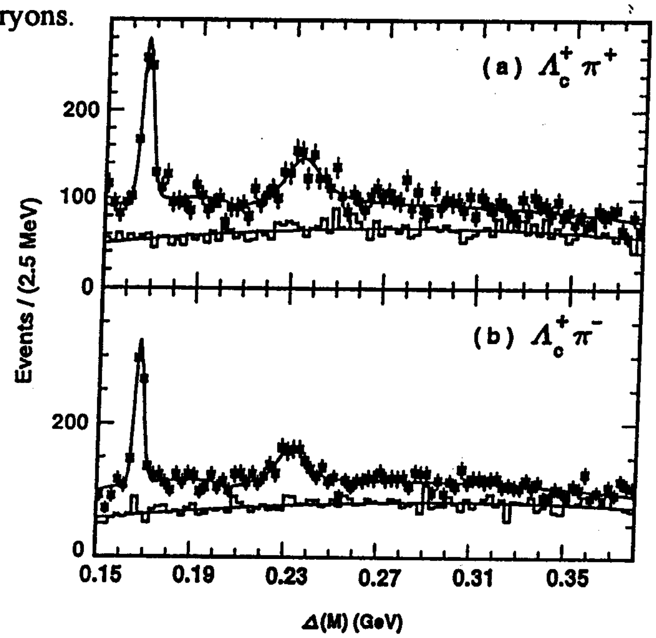

Figure 7. Inv. mass difference distrib. of (a) $\Lambda_c^+\pi^+$ and (b) $\Lambda_c^+\pi^-$ combinations with $x_p > 0.5$.

OBSERVATION OF $\Lambda_{c1}^{**+}(1/2^-)$ AND $\Lambda_{c1}^{**+}(3/2^-)$

In the case of the ground state $\Lambda_c^+(cud)$ charmed baryon, the orbital angular momentum quantum number between the light quarks and that between the heavy charm quark and the light diquark, denoted as l and l', are both equal to zero. If the orbital angular momentum between the charm quark and the diquark is excited to $l = 1$, two orbitally excited states $\Lambda_c^{**+}(1/2^-)$ and $\Lambda_c^{**+}(3/2^-)$ are expected, with the $(3/2^-)$ state expected to be more massive than the $(1/2^-)$ one. Both states can decay via $\Sigma_c\pi$; but the $(1/2^-)$ state has an S-wave decay while the $(3/2^-)$ state has a D-wave decay. In 1993, ARGUS[24] reported the observation of a resonant state decaying into $\Lambda_c^+\pi^+\pi^-$ at a mass difference $\Delta M^+ = M(\Lambda_c^+\pi^+\pi^-) - M(\Lambda_c^+) = 341.5 \pm 0.6 \pm 1.6\ MeV/c^2$. Not long after, E687[27] at FNAL reported a similar observation with a mass difference of $340.4 \pm 0.6 \pm 0.3\ MeV/c^2$.

The CLEO[31] analysis is based on 3 fb^{-1} of data in the region of the $\Upsilon(4S)$. A Λ_c^+ sample is obtained using six different decay modes: $pK^-\pi^+$, $p\overline{K^0}$, $\Lambda\pi^+$, $\Lambda\pi^+\pi^0$, $\Lambda\pi^+\pi^+\pi^-$ and $\Sigma^+\pi^+\pi^-$. In Figure 8, we show the mass difference distribution $\Delta M^+ = M(\Lambda_c^+\pi^+\pi^-) - M(\Lambda_c^+)$ for all $\Lambda_c^+\pi^+\pi^-$ combinations with $x_p > 0.7$. Two clear peaks can be seen.

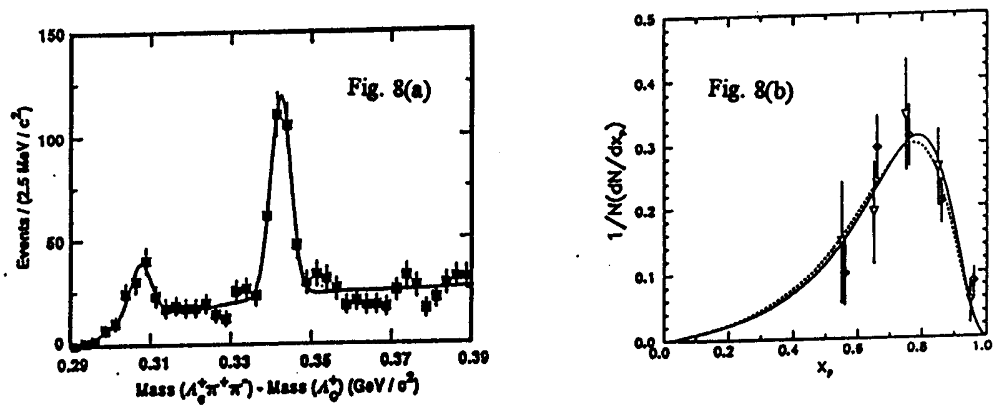

Figure 8. (a) Inv. mass distrib. for $\Lambda_c^+\pi^+\pi^-$ combinations with x_p>0.5. (b) x_p production spectrum with Peterson function fit.

A fit using Briet-Wigner line shape convoluted with a Gaussian detector mass resolution yields signal sizes of 112.5 ± 16.5 and 244.6 ± 19.0 events at mass differences of $307.5 \pm 0.4 \pm 1.0$ and $342.2 \pm 0.2 \pm 0.5$ MeV/c^2 and natural widths $\Gamma_l = 3.9^{+1.4+2.0}_{-1.2-1.0}$ and $\Gamma_h < 1.9$ MeV/c^2, respectively. The two resonances are commonly referred to as the $\Lambda_c^{**+}(2593)$ and $\Lambda_c^{**+}(2625)$ excited states. The fraction of Λ_c^+'s from the secondary decays of these states has been measured to be $(1.44 \pm 0.24 \pm 0.30)\%$ and $(3.51 \pm 0.34 \pm 0.28)\%$, respectively. From the study of $\Lambda_c\pi$ mass distributions, CLEO measures the branching fraction of Λ_c^{**+} (2593) to $\Sigma_c^{++}\pi^-$ and $\Sigma^0\pi^+$ to be $(36 \pm 09 \pm 09)\%$ and $(42 \pm 09 \pm 09)\%$, respectively. There is no evidence for the $\Lambda_c^{**+}(2625)$ to be decaying through the $\Sigma_c\pi$ channel. Thus the lower mass state is identified as the $(1/2^-)$ and the higher mass state as the $(3/2^-)$ state.

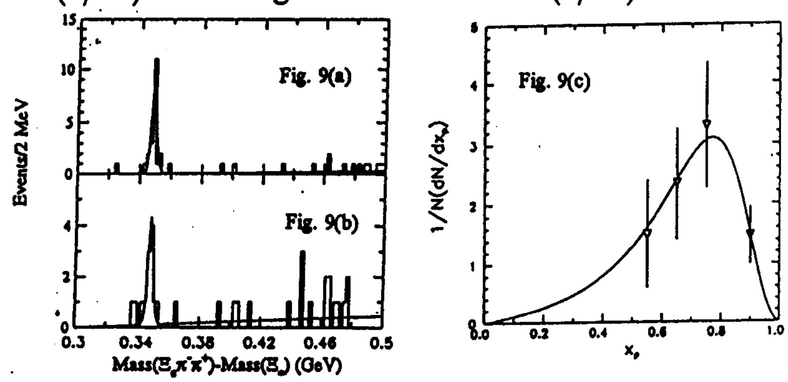

Figure 9. Inv. mass distrib. for $\Xi_c^{*0}\pi^+$ and $\Xi_c^{*+}\pi^-$ combinations with x_p>0.5. x_p production spectrum averaged over the two states and fit to Peterson function.

OBSERVATION OF $\Xi_c^{**+}(3/2^-)$ AND $\Xi_c^{**0}(3/2^-)$

The lowest orbitally excited states of the $\Xi_c(csq)$ are obtained by putting the heavy quark with an angular momentum quantum number $l = 1$ with respect to the light diquark. Two sets of states with $J = (1/2^-)$ and $J = (3/2^-)$ are expected. CLEO[42] reported the first observation of two resonances decaying to $\Xi_c^{*0}\pi^+$ and $\Xi_c^{*+}\pi^-$, which may be interpreted as the most likely candidates for the $\Xi_c^{**}(3/2^-)$ isospin doublet. Using 4.8 fb^{-1} of data in the region of the $\Upsilon(4S)$, the analysis starts by defining Ξ_c^{*+} and Ξ_c^{*0} candidates using the decay sequence $\Xi_c^0\pi^+$ and $\Xi_c^+\pi^-$, respectively. The Ξ_c^0 is detected in the decay modes: $\Xi^-\pi^+$, $\Xi^-\pi^+\pi^0$, $\Lambda\overline{K^0}$, $\Xi^0\pi^+\pi^-$, $\Omega^-\pi^+$ and $\Lambda K^-\pi^+$. The decay modes $\Xi^-\pi^+\pi^+$, $\Xi^0\pi^+\pi^0$ and $\Lambda\overline{K^0}\pi^+$ are used for reconstructing Ξ_c^+. Combining Ξ_c^* candidates with the charged pions in the event, the mass differences $\Delta M^+ = M(\Xi_c^{*0}\pi^+) - M(\Xi_c^{*0})$ and $\Delta M^0 = M(\Xi_c^{*+}\pi^-) - M(\Xi_c^{*+})$ are calculated. In Figure 9, the mass difference distributions ΔM^+ and ΔM^0 for combinations with $x_p > 0.6$ are plotted. Two very clean peaks with little background can be seen. Fitting these peaks with a Breit-Wigner convoluted with a Gaussian detector resolution yields signal areas of 18.8 ± 4.4 and 9.5 ± 3.2 events at mass differences of $348.5\pm0.5\pm1.0$ and $348.1 \pm 0.8 \pm 1.0$ MeV/c^2, respectively. The corresponding natural widths are measured to be $\Gamma^+ < 3.5$ and $\Gamma^0 < 8.1$ MeV/c^2, respectively. Assuming the production spectrum of the charged and neutral member to be the same, a fit to the averaged x_p spectrum with a Peterson function returns the value $\epsilon_Q = 0.07^{+0.03}_{-0.02}$,which is similar to the corresponding value for the orbitally excited Λ_c^{**+}'s reported earlier. These states are associated with the $(3/2^-)$ states rather than the $(1/2^-)$ states, as in this case, the decays proceed through an S-wave rather than a D-wave that would be required in the second case, which would be suppressed. The measured mass differences are consistent with recently published theoretical calculations[43] [44] .

SUMMARY AND CONCLUSION

We may summarize our results as follows. Most of the singly-charmed ground-state baryons have been found. Only the Σ_c^{**0} and the Ω_c^{*0} have not been seen. Using the newly reprocessed data along with data from CLEO II.5 may yield these signals soon. Masses and isospin mass splittings have been measured. Using the lowest masses as input, various models are successful at predicting the higher mass members. The isospin mass splitting measurements are limited in statistics. The theoretical calculations are also limited in their predictive power, even the sign of the splitting varies from model to model. Orbitally excited charmed baryons are beginning to pop up. The Peterson function is a good representation of the x_p production spectrum. The x_p spectra of all the ground-state baryons can be fit to Peterson functions with ϵ_Q parameter between $0.2 - 0.3$, while those of the orbitally-excited members require values of ϵ_Q between $0.05 - 0.07$. A substantial fraction of ground-state baryons are produced from the secondary decays of higher mass states and so they have softer spectra. Doubly charmed baryons may remain out of reach for the present CLEO data set. Fermi National Accelerator Lab and the LHC at CERN may have easier access to these higher mass states. Although the spectroscopy of ground-state baryons appears to be nearing completion, measurement of the branching fractions has just begun. **In conclusion, it would appear that CESR has already become a charmed baryon factory.**

REFERENCE

[1] J. E. Augustin et al., Phy. Rev. Lett., **33**, 1406 (1974).
[2] J. J. Aubert et al., Phy. Rev. Lett., **33**, 1404 (1974).
[3] E. G. Cazzoli et al., Phy. Rev. Lett., **17**, 1125 (1975).
[4] G. Goldhaber et al., Phy. Rev. Lett., **37**, 255 (1976).
[5] I. Peruzzi et al., Phy. Rev. Lett., **37**, 569 (1976).
[6] B. Knapp et al., Phy. Rev. Lett., **37**, 882 (1976).
[7] G. S. Abrams et al., Phy. Rev. Lett., **44**, 10 (1980).
[8] M. Calicchio et al., Phy. Ltrs. **93B**, 521 (1980).
[9] C. Peterson, Phy. Rev **D27**, 105 (1983).
[10] S. F. Biagi et al., Phy. Letts. **122**, 455 (1983).
[11] S. Biagi et al., Zeitschr. f. Phys. **C28**, 175 (1985).
[12] CLEO Collaboration: D. Bortolleto et al., Phy. Rev **D37**, 1719 (1988).
[13] CLEO Collaboration: T. Bowcock et al., Phy. Rev. Lett., **62**, 1240 (1989)
[14] CLEO Collaboration: P. Avery et al., Phy. Rev. Ltrs., **62**, 863 (1989).
[15] CLEO Collaboration: M. S. Alam et al., Phy. Ltrs. **B226**, 401, (1989).
[16] CLEO Collaboration, P. Avery et al., Phy. Rev. **D43**, 3599 (1991).
[17] CLEO Collaboration: S. Henderson et al., Phy. Lett. **B283**, 161 (1992).
[18] CLEO Collaboration: G. Crawford et al., Phy. Rev **D45**, 752 (1992)
[19] H. Albrecht et al., Phys. Letts. **B288**, 367 (1992).
[20] CLEO Collaboration: G. Crawford et al., Phy. Rev. Lett., **71**, 3259 (1993)
[21] CLEO Collaboration: P. Avery et al., Phy. Rev. Lett., **71**, 2391 (1993).
[22] CLEO Collaboration: Y. Kubota et al., Phy. Rev. Lett., **71**, 3255 (1993).
[23] CLEO Collaboration: P. Avery et al., Phy. Letts. **B325**, 267, (1993).
[24] ARGUS Collaboration: H. Albrecht et al., Phy. Letts. **B317**, 227 (1993).
[25] E-687 Collaboration: P. L. Frabetti et al., Phy. Letts. **B300**,190 (1993)
[26] CLEO Collaboration: T. Bergfeld, et al., Phy. Letts. **B323**, 219 (1994).
[27] E-687 Collaboration: P. L. Frabetti et al., Phy. Letts. **B338** ,106 (1994).
[28] CLEO Collaboration: R. Ammar et al., Phy. Rev. Letts., **74**, 3534 (1995).
[29] CLEO Collaboration: J. P. Alexander et al., Phy. Rev. Letts. **74**, 3113 (1995).
[30] CLEO Collaboration: J. P. Alexander et al., Phy. Rev. Letts. **74**, 3113 (1995) Erratum.
[31] CLEO Collaboration: K. W. Edwards et al., Phy. Rev. Letts. **74**, 3331 (1995).
[32] M. J. Savage, Phy. Letts., **B359**, 189 (1995).
[33] CLEO Collaboration: P. Avery et al., Phy. Rev. Let. **75**, 4365 (1995)
[34] CLEO Collaboration: L. Gibbons et al., Phy. Rev. Let. 77, 810 (1996).
[35] A. Falk, Phy. Rev. Lett., **77**, 223 (1996).
[36] CLEO Collaboration: T. Bergfeld et al., Phy. Letts., **B365**, 431 (1996).
[37] CLEO Collaboration: K. Edwards et al., Phy. Letts. **B373**, 261 (1996).
[38] CLEO Collaboration: J. P. Alexander, et al., Phy. Rev **D53**. Rapid Comm., R1013, Feb., 1996.
[39] CLEO Collaboration: T. Bergfeld et al., Phy. Rev. Lett., **77**, 4503 (1996).
[40] CLEO Collaboration: M. S. Alam et al., Phy. Rev **D57**, 4467, 1998.
[41] CLEO Collaboration: T. Bergfeld et al., European Physical Society Conference, 1997.
[42] CLEO Collaboration: M. Athanas et al., Int. Conference on High Energy Physics 98/866, 1998.
[43] D. Pirjol and A. FalkFalk, Phy. Rev. **D56**, 5483 (1997).
[44] G. Chiladze and T-M. Yan, Phy. Rev. **D56**, 6738 (1997).